

CONSTRAINTS IMPOSED BY ACID SULFATE SOILS
ON THE GAMBIA'S BRIDGE-BARRAGE SCHEME

by

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International Programs Report No. 5
Great Lakes and Marine Waters Center
The University of Michigan
Ann Arbor, Michigan

1985

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INTRODUCTION

The proposal to build an anti-salinity barrage across the Gambia River promises to initiate many and profound ecological changes. Not the least of these is the possible formation of a large area of acid sulfate soils.

Soils of many tropical estuaries have been found to contain appreciable amounts of unoxidized sulfidic material, usually in the form of pyrite, i.e., cubic iron II disulfide (FeS_2), and have a low acid buffering capacity. When attempts are made to reclaim these soils for agriculture, the sulfur becomes oxidized, producing large quantities of sulfuric acid. The soil pH drops, sometimes below 2.0, which endangers terrestrial and aquatic life; they have become acid sulfate soils.

This little understood phenomenon has come under intensive study in recent years as developing countries, notably in West Africa and Southeast Asia, have used modern techniques to reclaim swamp lands. Pressure to reclaim these lands has increased in West Africa and Southeast Asia in particular because of the recent droughts and a desire to increase domestic food supplies. Rice and/or fish production in these reclaimed lands has often been stymied by severe and unexpected acidity problems arising from acid sulfate soils.

Acid sulfate soils are not one of the world's major problem soils because of their limited areal extent. Taking the FAO/UNESCO estimation of 13 million hectares, they constitute only 1% of the world's cultivated land. Furthermore, the area is minor compared to that of saline or sodic soils and peat soils, both of which present more refractory problems than acid sulfate soils (Table 1). However, the problem is not as minor as these data might suggest. The data in Table 1 are probably severe underestimates of the true

TABLE 1. World distribution of some problem soils (million ha).¹

Region	Type of Soil		
	Acid Sulfate	Peat	Saline/Sodic
Asia and Far East	6.7	23.5	18.5
Africa	3.7	12.2	69.5
Latin America	2.1	7.4	59.4
North America	0.1	117.8	16.0
Near and Middle East	0.0	0.0	53.1
Australia	0.0	4.1	84.7
Europe	0.0	75.0	20.7
World Total	12.6	240.0	322.9

¹ Based on data from FAO/UNESCO soil map of the world.

magnitude of the problem because just about all acid soils occur in the developing world where soil maps are incomplete. Kawalec (1973) suggested 6.7 million hectares is a closer approximation of the acid soil area in Africa, almost double the FAO/UNESCO estimate. In addition, acid soils often occur in places where they cause maximum inconvenience, i.e., in tropical or sub-tropical estuaries adjoining intensively cultivated land. Under these conditions population pressure may make cultivation on acid soils essential and the problem, even though transient, is of critical dimensions.

In The Gambia concerns have been raised that construction of an anti-salinity barrage across the river will engender unmanageable soil acidity problems. Stopping salt water intrusion will lead to the drainage and subsequent oxidation of upstream acid soil areas during periods of low fresh-water flow, yielding acid. The acid produced will not only threaten agriculture but, because the acid runoff will be accumulated behind the barrage, threaten the entire riverine ecosystem.

Because the problem was perceived rather late in the planning of the barrage, it was necessary to reconsider the design, placement, and operation

of the barrage. Consultants have offered differing opinions from the recommendation to allow runoff acid waters through the barrage with the reassurance that reservoir pollution is "not considered likely to become critical" (Thomas et al. 1979) to the prediction that the pH in the reservoir may fall below 2.0 (Coode and Partners 1979).

Because the subject of acid soils is still somewhat obscure, it is the purpose of this report to serve as an introduction to the subject and especially to:

1. Describe the genesis, classification, and distribution of acid sulfate soils.
2. Describe their particular genesis in The Gambia and the constraints they impose on the barrage scheme.

CLASSIFICATION

Soils are classified according to a complete and comprehensive system based on the theory that each soil has a definite morphology which is related to the circumstances in which it was formed. The system borrows terminology from biological systematics having "classes, orders," etc. The primary objective of this system is to make it possible that each soil can be placed somewhere within a worldwide taxonomic system. The definitive publication for this system is Soil Taxonomy, produced by the U.S. Department of Agriculture (1975). Acid sulfate soils do not fit smoothly into this system. The chemical dynamics which govern their formation are very rapid in comparison to the slowly developing properties which are the normal criteria for soil taxonomy. At present the kind of acid soils found in The Gambia, for instance, would be

classified "typic sulfaquent," but this is still under discussion (Paramanathan and Gopinathan 1982).

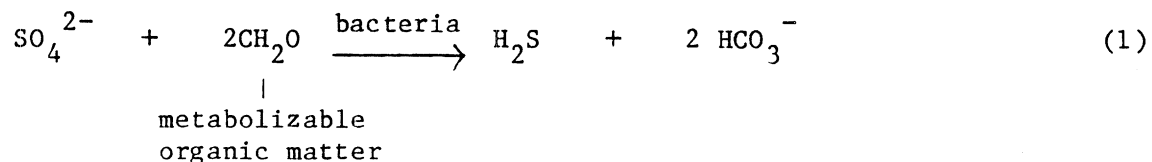
In this report the intricacies of soil taxonomy are avoided as inappropriate and the terms "potential acid sulfate" and "acid sulfate" are used throughout. To characterize these soils it is useful to define two terms from Soil Taxonomy. 1. Sulfidic material: waterlogged mineral or organic soil materials with $>0.75\%$ sulfur and less than three times as much carbonate (CaCO_3 equivalent) as sulfide sulfur. 2. Sulfuric horizon: mineral or organic soil material with a $\text{pH} < 3.5$ and yellow Jarosite mottles.

Potential acid sulfate soils, then, are those soils with sulfidic material above 1-m depth. Acid sulfate soils have a sulfuric horizon within 50-m depth. Soil Taxonomy's definition of sulfidic material contains the implicit assumption that the acid neutralizing capacity of the soil not including carbonate is equivalent to 0.75% sulfur. This is a reasonable limit (Van Breeman 1982), but the actual buffering capacity of these soils varies widely depending on texture and clay mineralogy. Bloomfield (1973) observed acid soils with only 0.1% sulfur.

GENESIS OF POTENTIALLY ACID SOILS

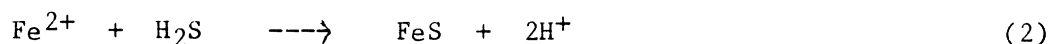
The "sulfidic material" referred to above is, except in rare instances, cubic iron II disulfide, FeS_2 , known as pyrite. The circumstances under which this mineral accumulates deserve scrutiny since they help to predict the whereabouts of potentially acid strata before the problem has arisen.

The first link in the chain of circumstances which leads to pyrite formation is the reduction of sulfate.

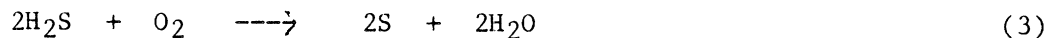


This reaction is accomplished by sulfate-reducing bacteria of the genera Disulfovibria and Disulfonaculum. These bacteria use sulfate during the oxidation of organic matter, for electron transport, in a manner analogous to the way in which respiring organisms use oxygen. The bacteria are anaerobes (they will only be found in anoxic environments) and require a near neutral pH (Thomas et al. 1979). If the bicarbonate waste of the reaction is not removed, not only will the bacterial activity be inhibited, but later acidification will not take place (Breemen 1973).

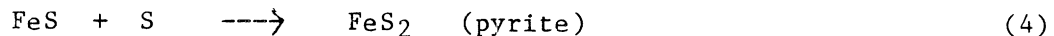
Hydrogen sulfide will react with any iron source to give iron II sulfide.



For the formation of pyrite to proceed beyond reaction 2 some hydrogen sulfide must be oxidized to sulfur. This can happen if the reduced soils periodically receive limited amounts of oxygen, for example, from sea water percolating through the soils at high tide (Pons and Breemen 1982).



then pyrite can be formed by



Reaction 3 will not occur exactly as written, but rather the oxygen is probably carried by iron II hydroxide as suggested by Thomas et al. (1979).

In marine environments sulfate is abundant and sulfate reducing bacteria are ubiquitous in reduced muds so only the availability of organic matter and iron will limit pyrite formation. The swamps flanking tropical estuaries provide all these ingredients. Dense vegetation (mangroves) detritus provides organic matter in anoxic muds, iron in sediments, and tidal inundation. Such a swamp soil can have three different redox regimes (Breemen and Pons 1978): (1) an aerobic surface layer; (2) a predominantly reduced layer underneath the surface which still has periods of limited aeration; and (3) a permanently reduced zone.

In the deepest part of a swamp the aerobic surface layer (zone 1) may not be present. It follows from the scheme of pyrite formation given above that pyrite can only be formed in zone 2. Therefore, it can be predicted that most pyrite will be found in conditions where zone 2 is thick. Work confirming this scheme has been conducted in Malaysia where little or no pyrite accumulation was found in zones 1 and 3. In areas crisscrossed by tidal creeks where tidal influence was strong, zone 2 was thick and pyrite contents were high. In soils along accretionary coasts with fewer tidal creeks, zone 2 was almost lacking and pyrite contents were much lower (Breemen and Pons 1978).

The accumulation of a significant amount of pyrite may take between 50 - 1,000 years. According to Breemen and Pons (1978), "There is some sedimentological and chemical evidence that pyrite formation rates in mangrove swamps may be in the order of 0.02% FeS_2 per year. Thus at least 50 years would be needed to produce 1% of pyrite." In rapidly accreting coasts conditions for pyrite formation may not persist long enough for a significant accumulation.

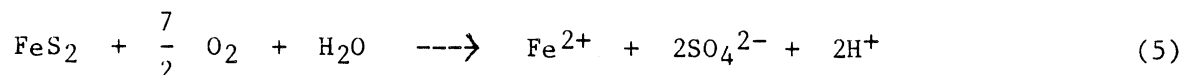
This is given by Pons and Breemen (1982) as one reason why acid sulfate soils are not found in Europe. They point out that sedimentation rates have been high since Roman times due to deforestation. On the other hand, they cite the lower potential acidity in recent sediments of the Mekong delta as evidence that this process is becoming more important in the tropics.

GENESIS OF ACID SOILS

The pyritic layer in soil is stable as long as the conditions of tidal flooding and a waterlogged environment persist. However, if drainage occurs and the water table stays below the pyritic zone for just a few weeks, then acidification will begin. The drainage may be brought about naturally by coastal accretion, or it may be induced much more rapidly by empoldering.

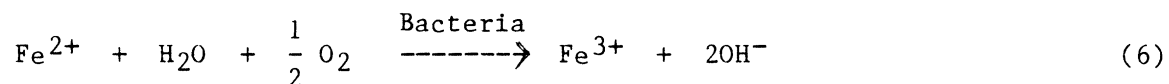
OXIDATION OF PYRITE

After drainage, oxygen will penetrate through cracks in the soil and the fine-grained pyrite typical of mangrove sediments is oxidized to iron II sulfate and sulfuric acid (Breemen and Pons 1978). The pH will drop to around 4.0.

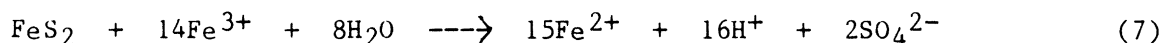


Many previous workers have reported this oxidation as being enhanced by bacteria of the genus Thiobacillus, especially T. thioparus. However, Arkesteyn (1980) found no effect of inoculation of various Thiobacilli on the initial rate of pyrite oxidation. "The role of Thiobacilli in enhancing initial pyrite oxidation and in causing the pH drop from near neutrality to pH 4.0 has probably

been overemphasized. Apparently the rate of pyrite oxidation in that range is determined by non-biological factors" (Breemen 1982).

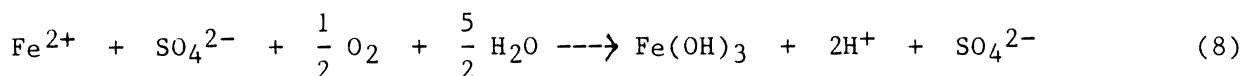


Iron II ions are oxidized to iron III slowly at low pH (Singer and Stumm 1970) but the thiobacillus T. ferrooxidans greatly enhances the rate. Iron III ions react rapidly with pyrite.

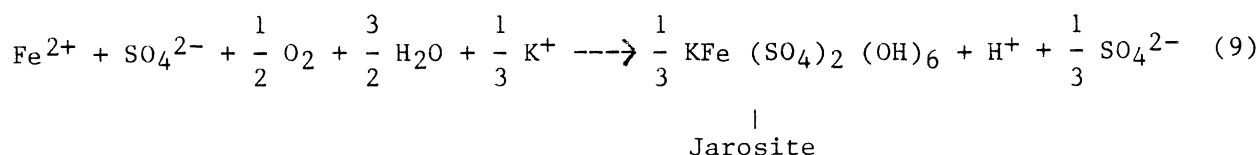


Reaction 7, which takes the pH down sometimes below 2.0, only operates at low pH because these levels suit the Thiobacilli (T. oxidans is most efficient between 2.5 and 5.5) (Thomas et al. 1979). Iron III compounds are not very soluble above pH 3.5, which explains why pyrite is rapidly oxidized at low pH. The immediate oxidation products are iron II ions, sulfate, and hydrogen ions (acidity). Most of these will undergo further reactions in the soil. Most of the sulfate remains in solution and is leached, and some will be precipitated in Jarosite. Hydrogen ions are inactivated by ion exchange and weathering.

Iron II ions will be oxidized to iron III and finally become incorporated into amorphous iron III oxide or Jarosite.



or



Neither Jarosite nor iron III can persist in the presence of pyrite because the iron III would be reduced as in equation 7 above. They are formed when iron II ions diffuse upward through the soil. Because both reactions 8 and 9 produce acid this may result in the acidification of the non-sulfidic top layer of soil (Breemen and Pons 1978). Both Jarosite and iron III oxide (red mottles) are important visual indicators of acid sulfate soils, especially the distinctive yellow mottles of Jarosite. Jarosite is more stable than iron III oxide at low pH (Breemen 1976) but will eventually hydrolyse to goethite. This may happen in a few months (Breemen 1976) or it may persist for many years (Verhoeven 1973).

RATE OF OXIDATION

The first physical-chemical oxidation takes place in about 1 month if the soil is well aerated. The pH drops from 7.0 to 4.0 due to the oxidation of about 0.5% sulfur (Breemen 1982). Within a few months of this the pH falls below 3.0 and often below 2.0 (Breemen and Pons 1978). Pyrite contents of 6% can be halved in this period and not all the sulfur goes to sulfate (Breemen 1976). Considerable amounts may be lost as sulfur dioxide gas, a chemical intermediate. The rate of oxidation slows considerably after this initial period, and in a well developed acid soil pyrite oxidation may hardly be noticeable (Breemen 1982). Several decades may be required for a pyrite layer to be completely removed.

The final pH of the soil depends on its mineral composition, the total sulfur content, and the circumstances under which it was drained. Breemen (1980) studied acid sulfate soils on the Bangkok Plain and found that the original clay minerals of the soil plus those found after acidification (iron

III oxide, Jarosite, basic aluminum sulfate, amorphous silica) make an excellent pH stat and the pH was stabilized in the range 3.6 - 3.8. If, however, acidification is very rapid, as in some reclamation schemes, the buffering mechanism breaks down and a lower pH is obtained. In The Gambia, Dent and Raiswell (1982) found a consistent relationship between "final" pH and percentage sulfur only when sulfur content was below about 1.8%. Sulfur contents above 1.8% produced pH in the range of 1.2 - 1.8 (Fig. 1).

EFFECTS OF ACIDIFICATION

Soil pH values below 4.0 will affect the growth of most plants. In Thailand an estimated 600,000 hectares of potentially acid soils were a major constraint on agricultural development. Attempts to grow transplanted rice on soils with a pH of 3.9 have failed, and all the plants quickly died (Attananda et al. 1982). Johnson (1978) predicted that in The Gambia acid conditions will "quickly" contribute to the destruction of all mangroves (8,700 ha) upstream from the anti-salinity barrage.

The major toxic effect of acid sulfate soil is not always acidity per se, but the mobilization of metal ions which are insoluble at higher pH, especially aluminum and iron. Figure 2 shows actual aluminum values at various pH in acid soils in Thailand. Figure 2 shows that, at pH 3.5, concentrations of aluminum were in the 40 - 50 $\text{mg}\cdot\text{L}^{-1}$ range. Thomas et al. (1979) used kinetic equations to predict that, in The Gambia, aluminum ion concentrations will be 43 $\text{mg}\cdot\text{L}^{-1}$ at pH 3.5. Concentrations as low as 1.7 $\text{mg}\cdot\text{L}^{-1}$ of aluminum have a toxic effect on rice. High aluminum concentrations affect cell division, disrupt enzyme systems, and hinder the uptake of nutrients (Breemen and Pons 1978).

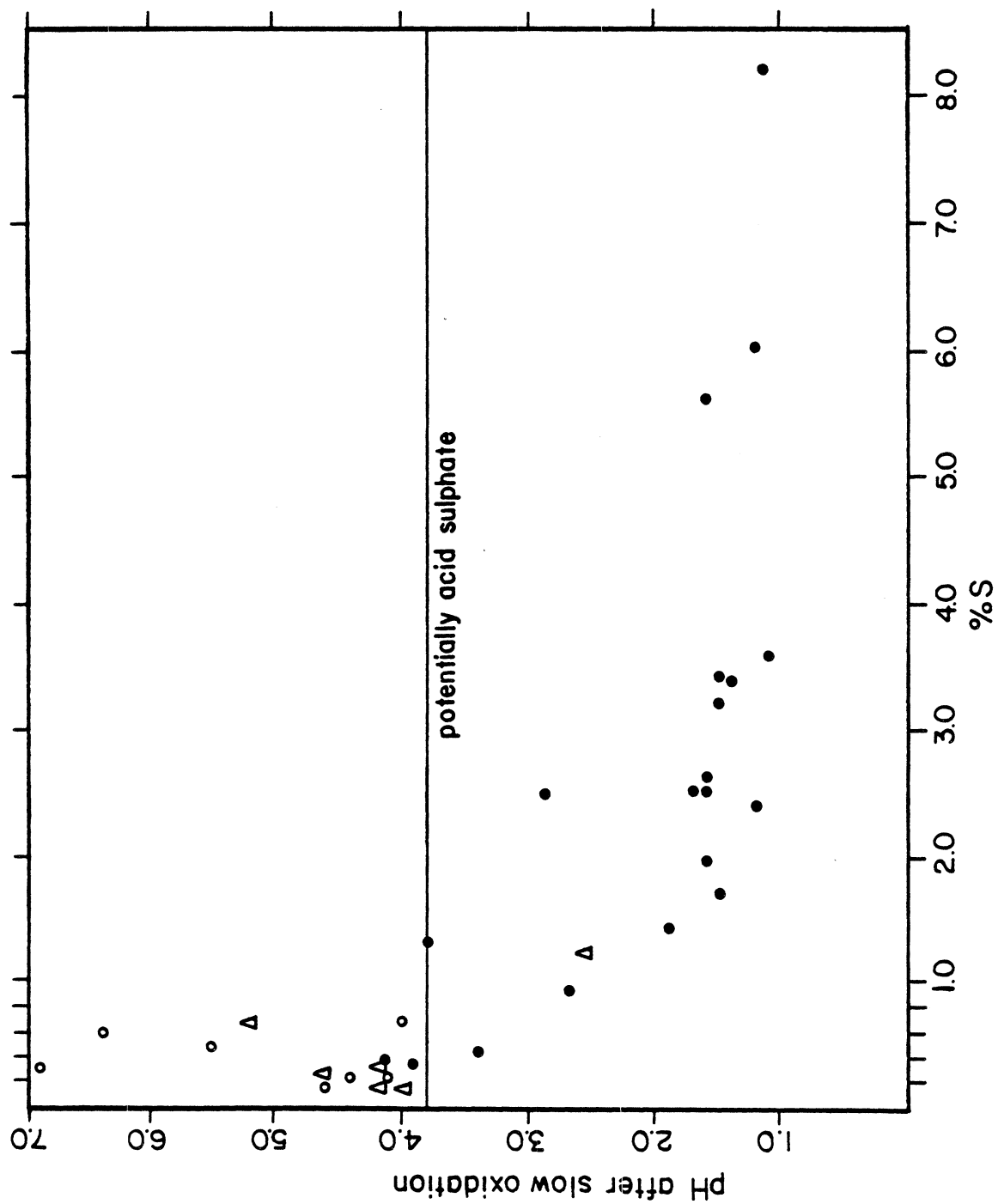


FIG. 1. Total sulfur content and pH values of samples after 2 years oxidation under moist conditions.

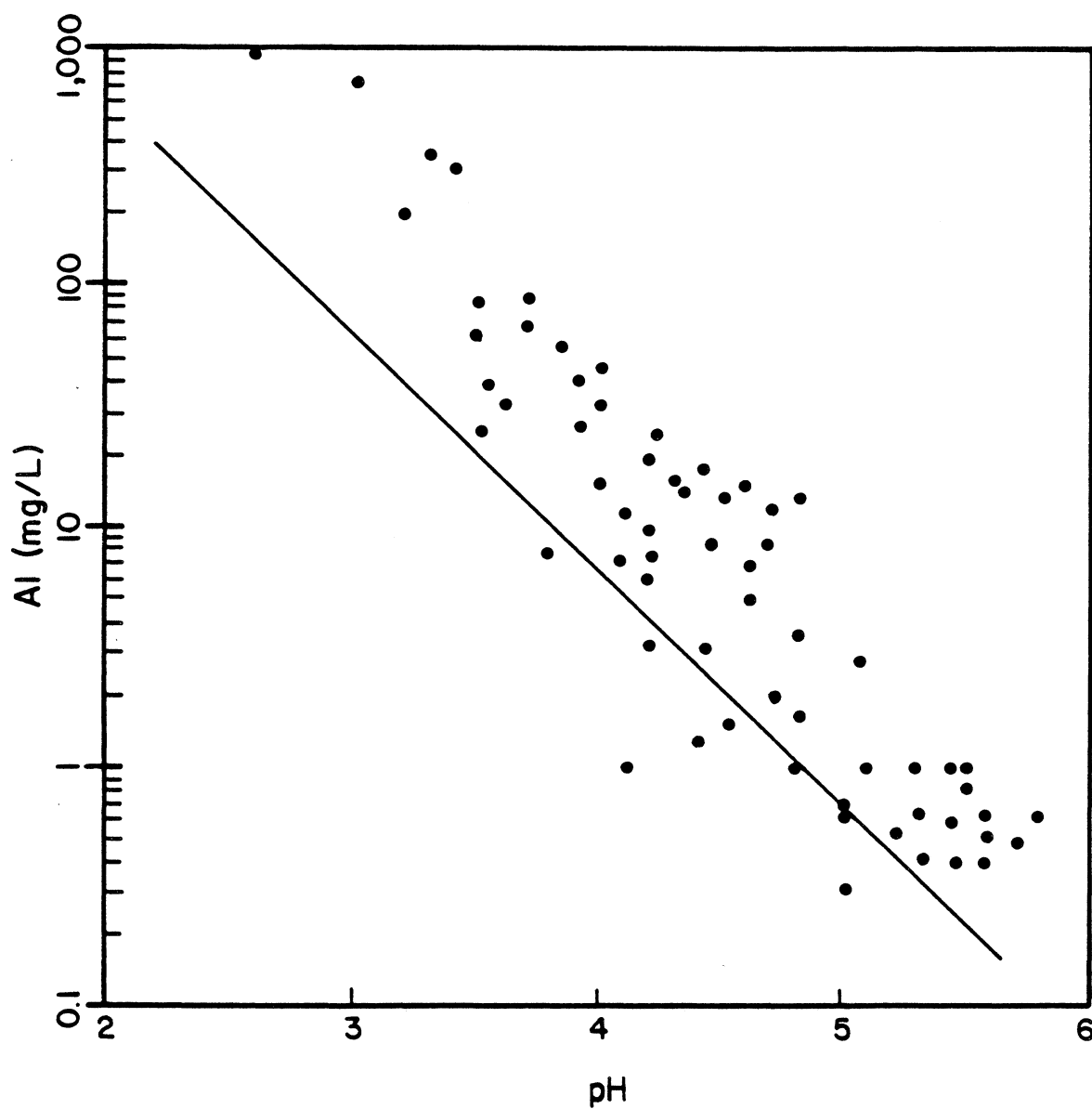


FIG. 2. Dots show dissolved aluminum versus pH in the soil solution of acid sulfate soils either untreated or amended by leaching, liming, or addition of MnO_2 , at various times after flooding. The solid line is for equilibrium with Al(OH)_3 , assuming that the activity of uncomplexed Al^{3+} amounts to 5% of total dissolved AL, at a SO_4^{3-} activity of 5×10^{-3} mol/liter. From Breemen and Pons (1978).

Iron II ions are toxic to rice in the 300 - 400 mg·L⁻¹ range. When an acid sulfate soil paddy is flooded, iron II ion values may rise to several thousand mg·L⁻¹. Toxic levels may persist for some time, because iron is less easily leached than aluminum (Breemen and Pons 1978). Acid soils are generally low in nutrients, especially phosphorus (Bloomfield and Coulter 1973). Acid drainage waters can effect neighboring rice fields on good soil.

IDENTIFICATION OF POTENTIAL AND ACTUAL ACID SOILS

According to the definition of sulfidic material (given above) in Soil Taxonomy, potential acid sulfate soils have at least 0.75% reduced sulfur. Using this definition, identification of acid sulfate soils is a matter for the soil analyst. But, there will almost inevitably be some oxidation before the sample can be analyzed unless it is thoroughly dried in the field (Thomas and Varley 1982), which is not always practical.

An alternative definition of the sulfidic material which comprises acid soils was put forward by Breemen (1982). "Sulfidic material is waterlogged mineral, organic, or mixed soil material with a pH of 3.5 or higher, containing oxidizable sulfur compounds which if incubated as a 1-cm layer under moist aerobic conditions at room temperature show a drop in pH of at least 0.5 units to a pH below 3.5 within 4 weeks." This definition allows the soil to "speak for itself" and is probably superior in that it emphasizes the essential property of acid soil (the pH drop) rather than the amount of sulfur. The method of identification follows from the definition although it is worth noting that the sample must be kept moist because the bacteria which speed the oxidation do not operate in dry soil.

In many instances an immediate indication of potential acid soil is useful. This can be achieved by the addition of 30% hydrogen peroxide. This strong oxidizing agent will cause an immediate pH drop of from 1.0 to 2.0 standard units if pyrite is present (B. Verhoeven, personal communication).

A seemingly useful field test utilized wooden poles coated with red lead in linseed oil. These were hammered into the ground, the theory being that pyrite would reduce the red lead causing blackening (lead sulfide). This technique would not only give the whereabouts of sulfidic layers but give the depth and thickness of the strata also. Unfortunately the test is not specific for pyrite but shows the presence of all water soluble sulfides common in reduced muds. Thomas and Varley (1982) used this method in The Gambia in conjunction with laboratory analyses. The technique was abandoned when it became clear there were many false positives. Coode and Partners relied on this method in their 1976 survey in The Gambia and were discovered to have overestimated the acid soil area by more than 30%.

Acid soils are easy to recognize using the essential characteristic of pH. If the soil has to be removed for pH to be taken in a laboratory, Thomas and Varley (1982) found that, even without precautions to protect a sample from air, etc., the pH will not show significant changes for about 1 month. Because Jarosite mottles are not inevitably present, Breemen (1982) has suggested that Soil Taxonomy's definition be amended to indicate that Jarosite is "generally present" but that acid sulfate soils always have more than 0.05% soluble sulfate.

AMELIORATION OF ACID SULFATE SOILS

A potentially acid soil can be used and preserved for agriculture by keeping the water table high. Once a soil has gone acid, however, there are really only two approaches to recovering it: neutralizing the acid or flushing it out.

Acid soils have been successfully reclaimed by neutralization with calcium carbonate (from limestone or marl). Verhoeven (1973) reported the successful use of lime on acid soils in the Wieringermeerpolder and said "apart from the very first years of farming the results were not too disappointing." The initial lime requirement was apparently 150 tons per hectare for the first 2 years and 30 tons per hectare for some years after. Bloomfield and Coulter (1973) had limited success in Sierra Leone using a combination of liming ($5 \text{ tons} \cdot \text{ha}^{-1}$) and leaching. The success was limited in the sense that a fair yield rice crop was produced. But they found liming had to be repeated the following year and declared the procedure prohibitively expensive for use on a large scale.

The acid does not need to be completely neutralized to grow crops on it. Charoenchamratcheep et al. (1982) reported some success in rice cultivation after liming to pH 4.7. This prevented aluminum toxicity and limited iron toxicity. Better results were obtained when phosphate fertilizer was also added. Many studies agree that liming in conjunction with fertilizer (especially phosphate and nitrogen) can make otherwise sterile acid soils productive, but rarely on an economic basis.

Theoretically, leaching after deep drainage will eventually remove all soil acidity, but this usually takes many years. An appreciable fraction of the acidity is immobile and the time necessary to remove it will depend on the

hydrology and hydraulic conductivity (usually low in these soils). Estimates vary from a few years to a century, although 20 to 30 years is reasonable. Leaching can be speeded up by digging deep drainage ditches.

ACID SOILS IN THE GAMBIA

The Gambia River is flanked on both sides by flat land which has led to the formation of large areas of mangrove swamp ramifying deeply into the surrounding country. These swamps receive waters from many creeks which have a large tidal amplitude. As pointed out by Pons and Breemen (1982), such swamps provide optimum conditions for pyrite formation because "the supply of new sediment is too small to cause rapid coastal accretion but high enough to prevent formation of pure peats."

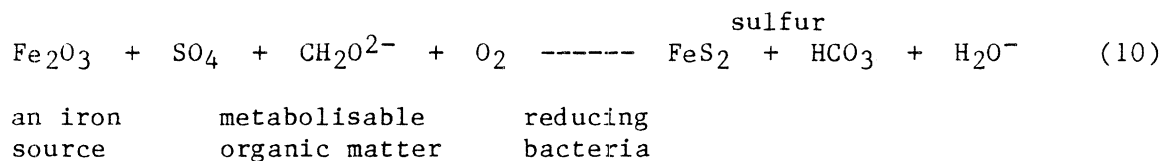
The two major mangrove species in these swamps are Rhizophora racemosa, tall trees generally seen at the edges of the main river and the creeks, and Avicennia africana, a shorter more bushy species found further inland on higher ground (Johnson 1978). Other species which may be found at the interface between these two include the Rhizophora species R. mangle and R. harisonii (Giglioli and Thornton 1965).

In The Gambia, as in the rest of West Africa, R. racemosa is usually the pioneer mangrove, which colonizes the virgin alluvium (Giglioli and Thornton 1965). Other species of mangrove usually succeed R. racemosa. The mechanism of succession seems to be that R. racemosa gradually develops a mat-like layer of root material on the surface of the soil. This collects detritus and encourages sedimentation. Thus over a period of time the land rises gradually above the water regime enjoyed by R. racemosa. R. racemosa will die and is then replaced, temporarily, by other species of Rhizophora, and finally by

Avicennia spp. (Giglioli and Thornton 1965). Giglioli and Thornton (1965) found that the creeks in the lower basin were generally bounded by R. racemosa up to the limit of daily tidal flooding and that Avicennia spp. extended beyond these to the average limit of spring tidal flooding.

There are at least three reasons for believing that, in The Gambia, the presence or absence of R. racemosa determines whether or not pyritic material will be found in a swamp soil. First, Rhizophora spp. have a much better developed root system than Avicennia. Hesse (1961) found that, while recently deposited alluvial soils contained 4.6% organic carbon and Avicennia muds contained 5.5%, Rhizophora muds contained up to 11.9%. Giglioli and Thornton (1965) found high percentages of carbon in Avicennia muds but attribute it to previous occupation by Rhizophora. Second, Thomas et al. (1979) found that in these soils sulfidic material is deeper farther from the river, perhaps a consequence of the mangrove succession described above. Third, Marius (1982) reported finding, in a survey of soils in Senegal and The Gambia, that most reduced sulfur occurs in micro-crystalline clusters of pyrite embedded in fibrous root remains of Rhizophora.

The requirements for pyrite formation can be summarized in the simplified equation:



In The Gambia, the decaying Rhizophora makes the mud anoxic for sulfur-reducing bacteria and provides organic matter. The tidal creeks provide sulfate, periodic oxidation, and flushing. Pyrite formation in these swamps

is an ongoing process and will continue into the future even above the barrage. Sulfate from sea water will be replaced by sulfates from neighboring acid soils.

DISTRIBUTION

Although potentially acid soils are present throughout the swamps of the lower river, only those above the barrage site will be affected by its construction. These soils were mapped in a study by the Land Resources Development Centre. Figure 3 is an adaption of their map (Thomas et al. 1979). The total area was 11,900 ha. Those soils flank the river to a distance of about 1,500 meters on both banks, between the barrage site at Balingho and about 35 km upstream at Pakali Ba. Above this there are only thin strips of sulfidic soil, mostly on the left bank, as far upstream as Jarreng, slightly over 70 km from the barrage site. Acid sulfate distribution closely follows mangrove distribution (Johnson 1978). These soils were overwhelmingly clays, with silt and sand particles absent or rare (Thomas et al. 1979). The clay consists mainly of kaolinite and silica (Dunsmore et al. 1976). Shells are rarely seen and acid buffering capacity is low.

The sulfic layer usually occurs within 50 cm of the surface of the soil and always within 1 m. The farther away from the river the deeper the layer. The ground level over this section of the river varies between 1.2 m and 1.8 m above Gambia Mean Datum; this fits the Coode and Partners (1979) estimate that the average depth of the sulfidic layer was 1.3 m above Gambia datum. Some of the soils above 1.3 m were subject to intermittent drying with no apparent acid production. This serves as additional confirmation that the sulfic layer does not begin until about 50 cm below the surface (Thomas et al. 1979). The

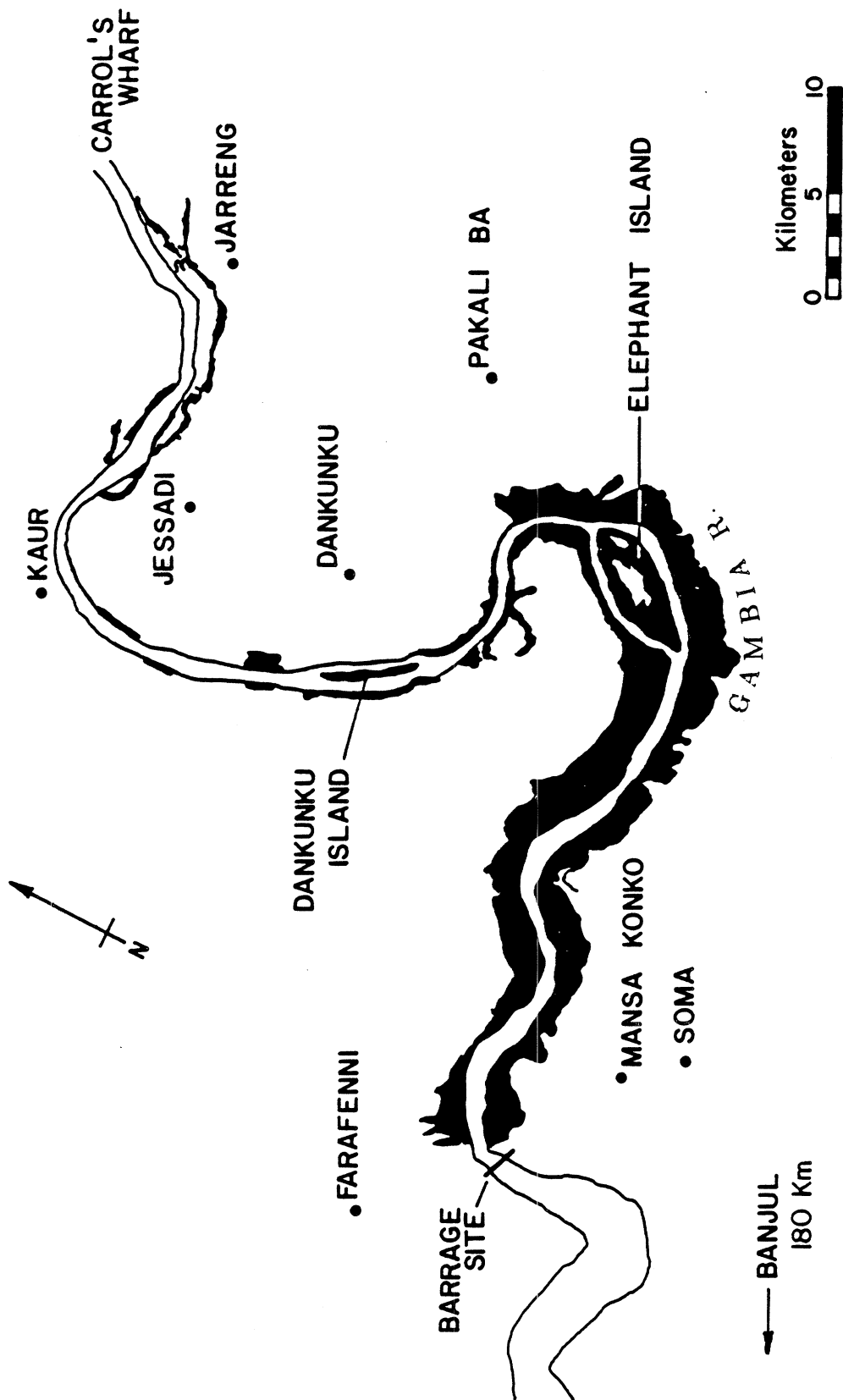


FIG. 3. Potential acid soils upstream of the proposed barrage. Adapted from Thomas et al. (1979).

amount of oxidizable sulfur in the sulfidic layer varies considerably, but the average of 2.5% was well in excess of the percentage required to cause a problem (Thomas et al. 1979).

ACTUAL SOIL ACIDIFICATION IN THE GAMBIA AND SENEGAL

Several small-scale reclamation projects have already encountered acidity problems in both Senegal and The Gambia. In The Gambia, pilot projects to extend existing rice growing areas by reclaiming mangrove swamp have been attempted at four locations in the Western Division: Pirang, Jibanack, Buruck, and Karantaba. All but one site rapidly developed soil acidity and could not successfully produce rice. The acidity of these soils has been monitored by the Department of Water Resources over a period of 6 months. The results were unequivocal examples of acid development in Gambian swamp soils. The discussion below of these four sites was drawn from Van Krimpen (1984, and personal communication).

At Burock a small (13 hectare) site was developed at the initiative of villagers along the mangrove belt near the village. This site was taken over and redesigned by the government which constructed a bund with four concrete sluice gates. After early failures, the government abandoned the site but the villagers managed to maintain a few plots by their own efforts. Thus, at the time of sampling there were two types of soils at the Burock site: (1) reclaimed plots, and (2) formerly reclaimed plots which had returned to natural conditions. Figure 4 shows the results of pH tests at three stations. It can be seen that the stations where natural conditions prevailed exhibited close to neutral pHs near the surface and slightly acid conditions lower down. Samples of these soils were incubated for 1 month under moist aerobic

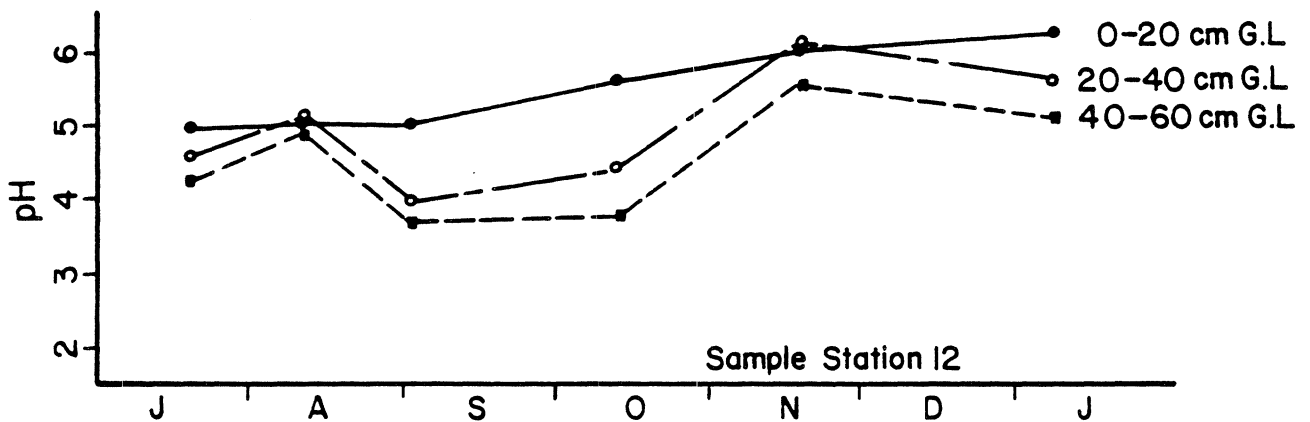
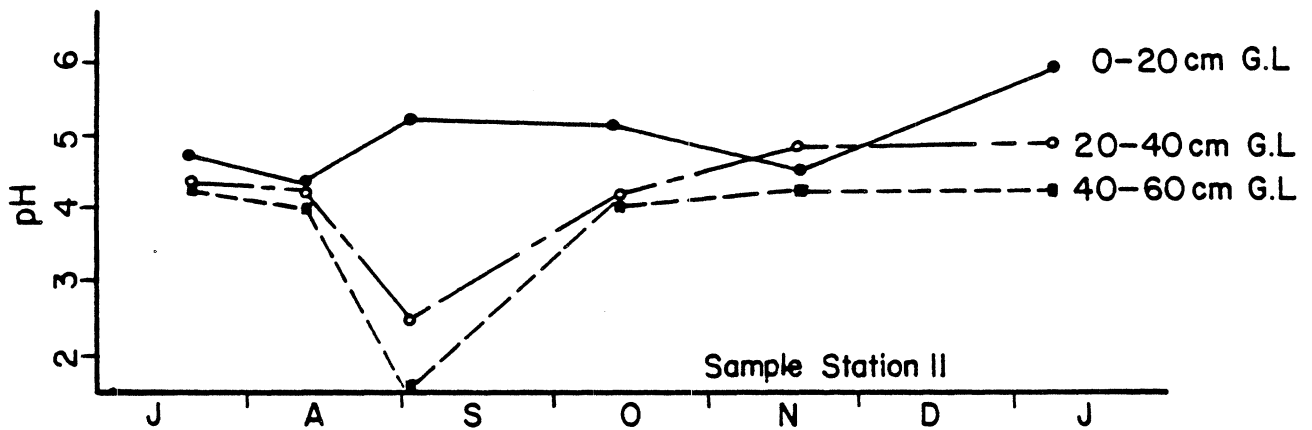
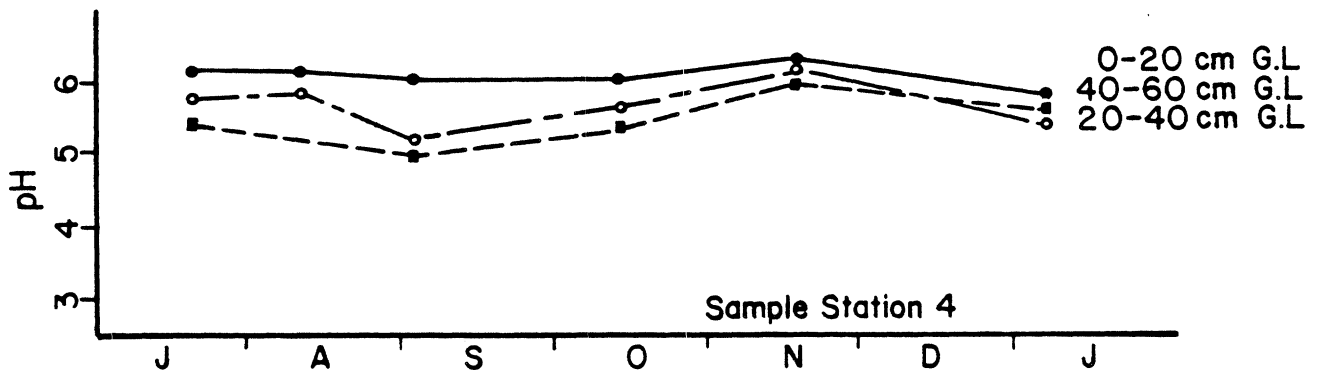


FIG. 4. Burock Scheme - sample stations no. 1, 4, 11, and 12. From Van Krimpen (1984).

conditions. They showed pH drops of 1.5 to 3.7 units, often to below pH 2. They were potential acid sulfate soils.

The protected station was quite acid during the entire sampling period, especially the lower levels. The acidity, which was maintained throughout the rainy season (June - October), was not all leached out. When samples of this soil were incubated the pH did not change significantly. The soil was acid sulfate and most of the pyrite had apparently been oxidized in the few months of drainage. These soils could no longer respond positively to the test for potential acidity, although this was not proven. Yellow mottling was not distinct, but rather the mottling varied from yellow orange to brownish red.

In Jibanack the bund excluding tidal waters was closed only shortly before sampling was begun and acid conditions developed very quickly (Fig. 5). The sharp rise in pH values in August was apparently due to heavy rainfall which flooded the area for some time.

The one location which did not develop severe acidity was Karantaba. This was anticipated since the location was more elevated than the others and is rarely flooded. The acidity occurred only in the deeper soils where there was also strong yellow mottling. Unfortunately, Karantaba's soils are saline and so even though the acidity is too deep to be toxic, rice crops have failed.

To make any of these acid soils productive will require costly fertilization and complex water management, the latter relying on rainfall which has been very erratic in this region of late. A feasibility study (Van Krimpen 1984) has recommended that they be abandoned.

In Senegal, small-scale rice production using traditional methods has for years grown rice in reclaimed swamp areas (Khouma and Touré 1982). They have

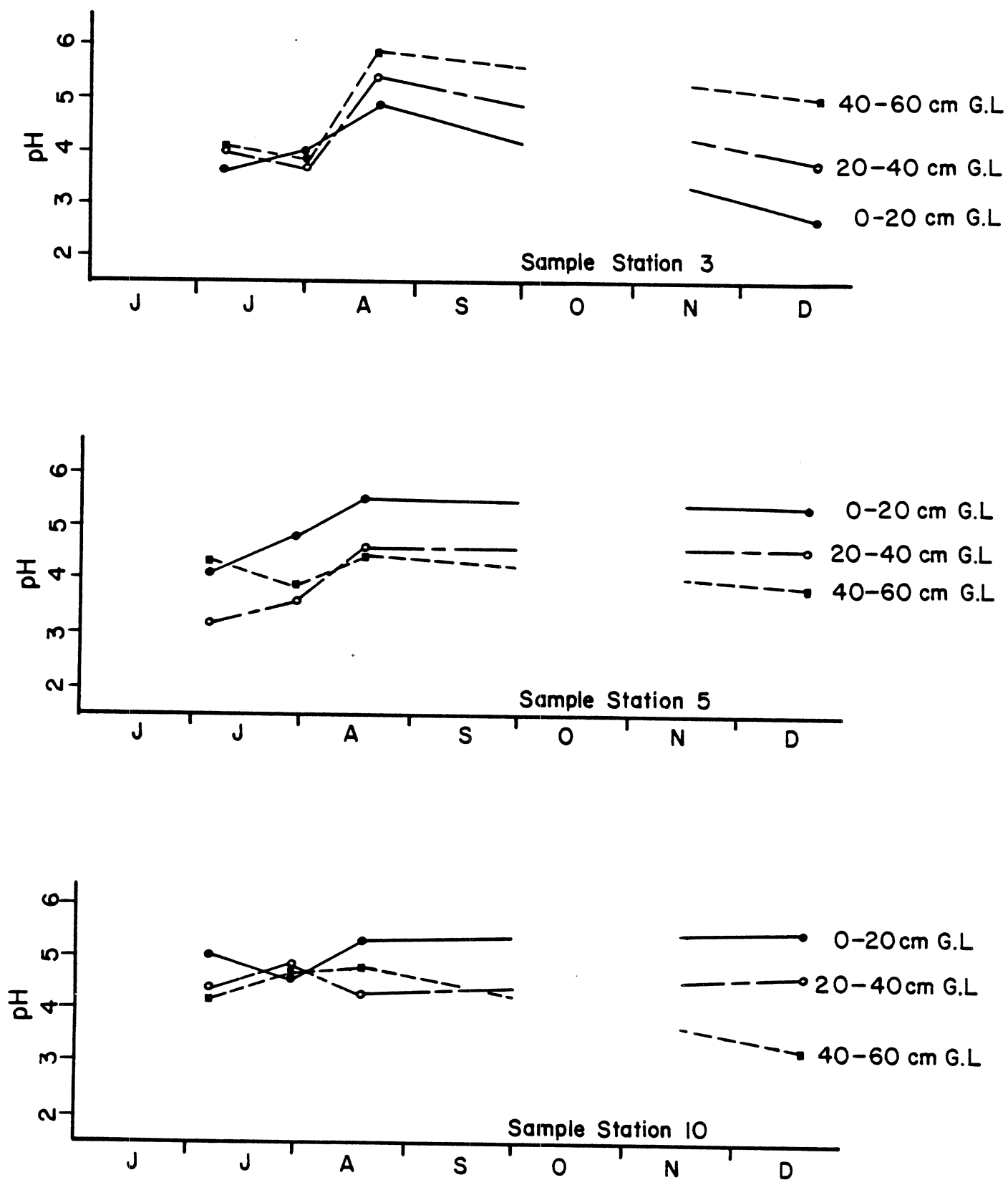


FIG. 5. Jibanack Scheme - sample stations no. 3, 5, and 10. From Van Krimpen (1984).

used raised beds of topsoil which were allowed to be flooded by tidal waters during the dry season and relied on the first rains to leach the accumulated salts. Thus they have avoided the problem of acidity but were very vulnerable to low rainfall or drought. In recent years these farmers have been persuaded, because of drought, to experiment with large-scale polders to exclude salt water all year. Designed only to deal with the problem of soil salinity, these projects have, for the most part, suffered from extreme acidity and have failed.

PROBABLE EFFECTS OF A BARRAGE AT BALINGHO ON ACID SOILS

The barrage will stop the intrusion of salt water up the Gambia River at Balingho while at the same time it will create a freshwater lake, which is intended to provide enough water to irrigate 24,000 hectares of land. Most of this new agricultural area will be used to grow rice in accordance with the Gambian government's declared aim of self-sufficiency in this staple food crop.

At present there are approximately 2,000 hectares of land upstream of the barrage site employed in irrigated rice production. This acreage will increase slowly after the barrage goes into operation. Coode and Partners (1979) suggested the cultivation of an additional 1,000 hectares per year as an attainable goal. Thus, the full cultivation program will not be reached until early next century.

As stated above, soils in the area of the reservoir have sulfidic material starting at + 1.3 Gambia mean datum (GD). Coode and Partners (1979) have estimated water levels of the lake under various rice irrigation schemes. Figure 6 shows that, irrespective of the amount of water withdrawn for

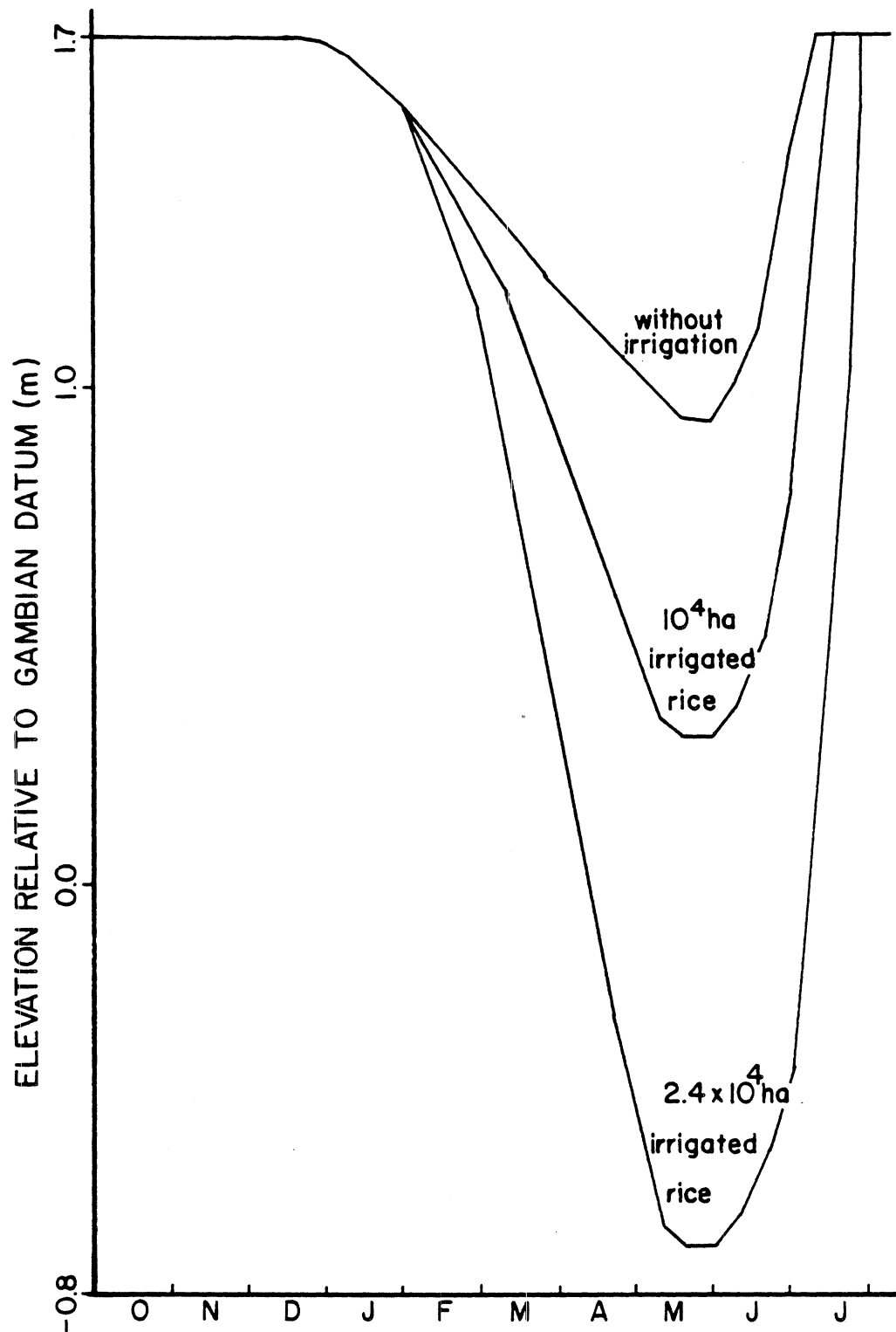


FIG. 6. Predicted reservoir water levels. Taken from Coode and Partners (1979).

irrigation, the water level will be below 1.3 GD for at least 3 months per year. This is enough time for the soils to develop acidic conditions.

The estimates in Figure 6 are not completely reliable and are probably low. There were no discharge data for the river in The Gambia. Coode and Partners (1979) used data from Goulombo and estimated run-off. The discharge values averaged over 7 years included 2 years of severe drought. Evaporation was calculated using open pan data, which probably gave a high estimate because weeds and rushes in the reservoir will lower the rate of evaporation.

In conclusion, acidity will develop sooner or later if the barrage is constructed, but it may not happen in the first few years. When acidity does develop because of low flow in one particular year, it will not necessarily occur the next year.

PROBLEMS ENGENDERED BY ACIDIFICATION

The acid soil problem in The Gambia has a unique aspect in that it is not soil acidity per se that is the major concern. There are approximately 35,600 hectares of land upstream of the barrage which are eminently suitable for rice production (Dunsmore et al. 1976), 11,000 hectares more than the reservoir could irrigate. At the moment almost all of the potentially acid soils support mangroves. These will die due to the changed water regime (Johnson 1978). Although the loss of 11,900 hectares of land because of soil acidity will cause inconveniences (small sections support rain-fed rice at present), it is not critical in the larger perspective of the barrage scheme. The major concern has been that the formation of acid sulfate soils will lead to unacceptable pollution of the reservoir. This could happen if very large amounts of sulfuric acid enter the river, by being leached from the soils by rain. Coode and

Partners (1979) used a mathematical model to predict the rate of pyrite oxidation and hence the amount of acid formed each year. They then calculated the reservoir pH if all this acid were transferred to the river, and predicted that between the barrage and Kaur the pH would be below 2.0. Dent and Raiswell (1981) modified this prediction slightly. Using a different model, but the same assumptions and data, they predicted pH ranging from 2.5 at the barrage site to 4.1 at Kaur (Fig. 7). If either of these predictions were correct, any barrage design which allowed acidification to take place would be unviable. All river life would be killed or seriously distressed and the acid waters would attack and corrode the concrete and steel of the barrage structure itself.

These predictions, fortunately, are probably inaccurate, and may be gross overestimations, because in the words of Thomas et al. (1979), they are "based on a number of theoretical models of dubious validity for the area." In more detail, the following objections can be raised to the Coode and Partners model, all of which, if sustained, would tend to lessen the pollution: (a) The area of acid soils is overestimated (17,600 ha as opposed to 12,800 ha; Thomas et al. 1979); (b) The percentage of unoxidized sulfur in the potential acid soils is overestimated (3.5% vs. 2-2.5%; Thomas et al. 1979); (c) It assumes that all the acid produced will be leached into the river, while in fact, a significant portion is immobile (Breemen 1980). Van Krimpen (1984) showed that acid soils lower down the river remained at constant pH throughout the rainy season, so leaching was certainly slow and not 100%; and (d) There seems to be no allowance for the buffering capacity of the water.

In a separate publication (Dent and Raiswell 1981), Coode and Partner's soil consultant says that "if only 10% of the acid were leached the pH (Fig. 7) would be one point higher." This could only be true if the buffering

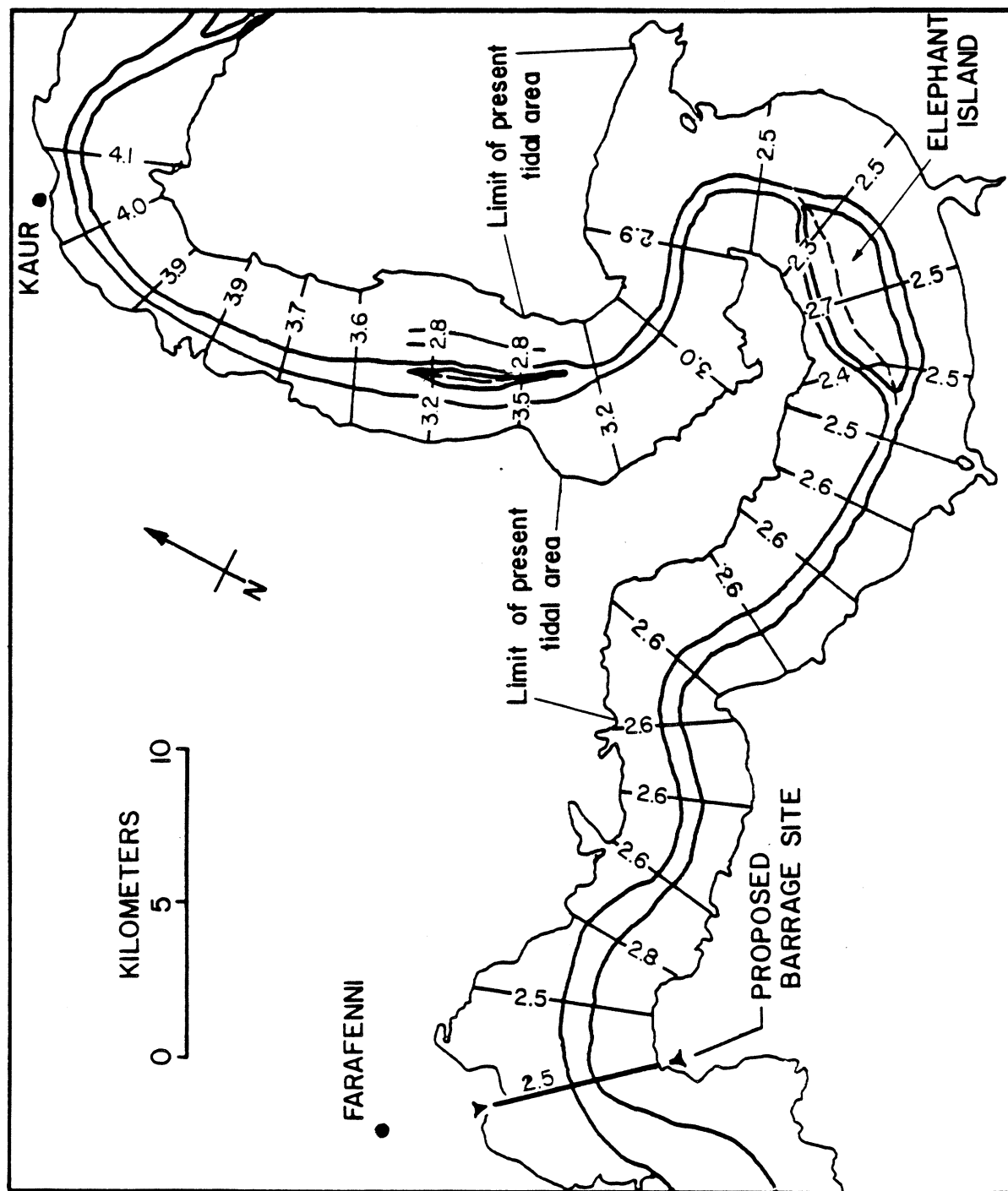


FIG. 7. Predicted pH values of the Gambia River upstream of the proposed barrage in mid-July, assuming abstraction of water for 24,000 ha irrigated rice. Taken from Dent and Raiswell (1982).

capacity of the water was insignificant. In fact, the alkalinity of the river at Bansang (away from salt water influence) is about $20 \text{ mg CaCO}_3 \cdot \text{L}^{-1}$ (Berry et al. 1985). The alkalinity of the waters entering the reservoir certainly will not be lower than this. Putting aside all the other objections to the Coode and Partners 2 model and accepting the figure of $2.71 \text{ moles} \cdot \text{m}^{-1}$ of H^+ (acid) which they say would enter the reservoir on the first year, it still appears that the alkalinity of the incoming waters (Coode and Partners' estimate) would be such that their pH could not go down to 5.1. Using Coode and Partners' assumptions and data, Johnson (1978) calculated average monthly inflow into the reservoir for June through October. These are the rainy season months during which acid may be flushed from the soil. A total inflow into the reservoir of 3.16 million cubic meters of water was estimated. If the average alkalinity of this incoming water was $20 \text{ mg CaCO}_3 \cdot \text{L}^{-1}$ (a minimum value according to Berry et al. 1985), total acid buffering capacity would be equivalent to 1.26×10^6 moles of H^+ . The acid sulfate area is 11,900 ha so the total acid would be 3.2×10^6 moles H^+ .

If there were complete mixing of incoming waters and acid, the resultant pH would be in the range 6.0-7.0. Dilution would ensure that high levels of sulfates are only likely to occur in the reservoir immediately at the start of the rains and be restricted to the stretch downstream from Dankunku Island. It is suggested that the problem could be solved by releasing the polluted water as early as possible (Thomas et al. 1979). Fears that "the ecological effects of the annual flush of acid will extend far downstream of the reservoir" by Dent and Raiswell (1981) are also unfounded. The buffering capacity of sea water is very high so that the effect on pH of mildly acidic reservoir water would be negligible.

CONCLUSIONS

In the first years after the barrage is closed, during the months of March, April, May, and part of June, the water level will fall such that potential acid soils will be drained and acid soils will be formed. Some of the acid will enter the reservoir and the pH will be depressed. The depth to which the soils will be drained cannot be predicted and the buffering capacity of the soil has not been determined, so that, in respect of the reservoir, it is considered impossible at this stage to predict the degree of pollution (Thomas et al. 1979) but it is unlikely to be extreme. Other undesirable effects include the speedy destruction of the mangrove area by the slumping of unripe muds, which are stabilized by mangrove roots, into the reservoir. Although hardly likely to affect the storage capacity, this infilling may give rise to navigational problems (Thomas et al. 1979). Some areas which are or could have been used for rain-fed rice production will be lost for an indeterminate period. None of these problems is of such severity as to be unmanageable. On the plus side, the acid soils can perhaps be reclaimed in about 20 years and once again be available for agricultural use.

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